Plate 6: Map of the Piezometric Surface of the Cameron Valley Sand Member (Lower Aquifer) of the Potomac Formation and Other Aspects of Urban Hydrogeology—Expanded Explanation
City of Alexandria, VA and Vicinity

By Anthony H. Fleming, 2015

Introduction

The geologic terrain occupied today by the City of Alexandria has been the site of major river systems at least sporadically since the *Potomac Formation* began being deposited during the early *Cretaceous*, about 131 million years ago (ma). Virtually the entire geologic record above the bedrock is the product of *fluvial* deposition and erosion. The most conspicuous elements in the modern landscape are the Potomac River, along with its major tributaries, Four Mile Run and Cameron Run. These three drainages ultimately control the hydrology of the city in myriad ways. The most obvious is in sheer volume: the amount of water flowing into and out of the city in these three streams every day accounts for a majority of the total water resource available in the city. All of the surface water that originates in the city ultimately drains into one of these three streams via a series of typically steep tributary ravines and a network of storm sewers (figure 6-1). During large storms, these *watersheds* receive *overland runoff* and a particularly large amount of direct *urban storm-water runoff*, which quickly transforms many of the smaller tributaries from placid ravines into raging torrents. Such flashy behavior is typical of urban streams.

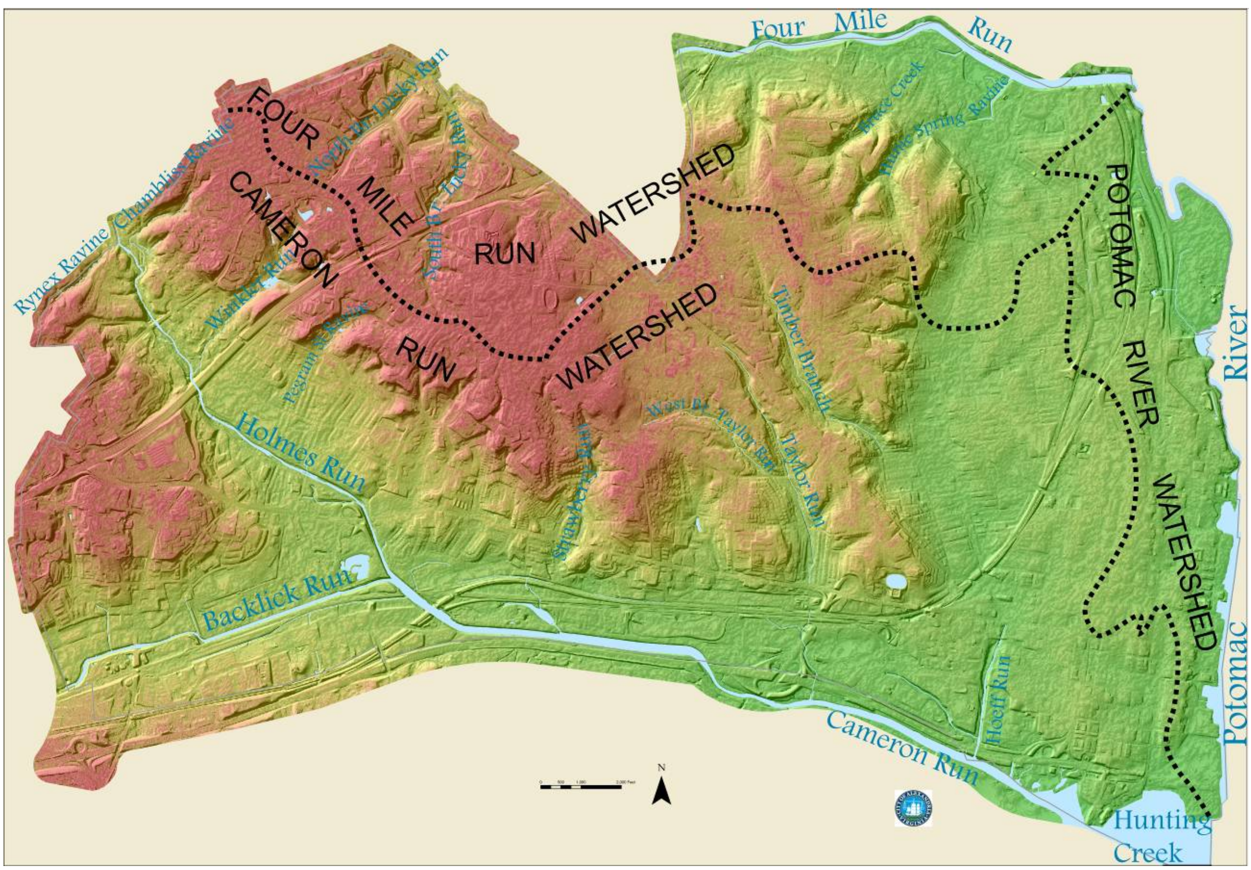


Figure 6-1. Major watersheds and drainage divides in the City of Alexandria.

On the other hand, a smaller but steadier volume of water flows largely unseen beneath the landscape as *ground water*, driven by the large elevation differential between the highlands in the western two thirds of the city and the valleys of the major drainages. The western highlands generally coincide with a major *piezometric* high—in essence, they act as a regional *ground-water recharge area*—and the eventual discharge of the ground water that originates there sustains the *base flow* of streams, ravines, and several wetlands in the city. Figure 6-2 illustrates the major components of the hydrologic cycle in the city.

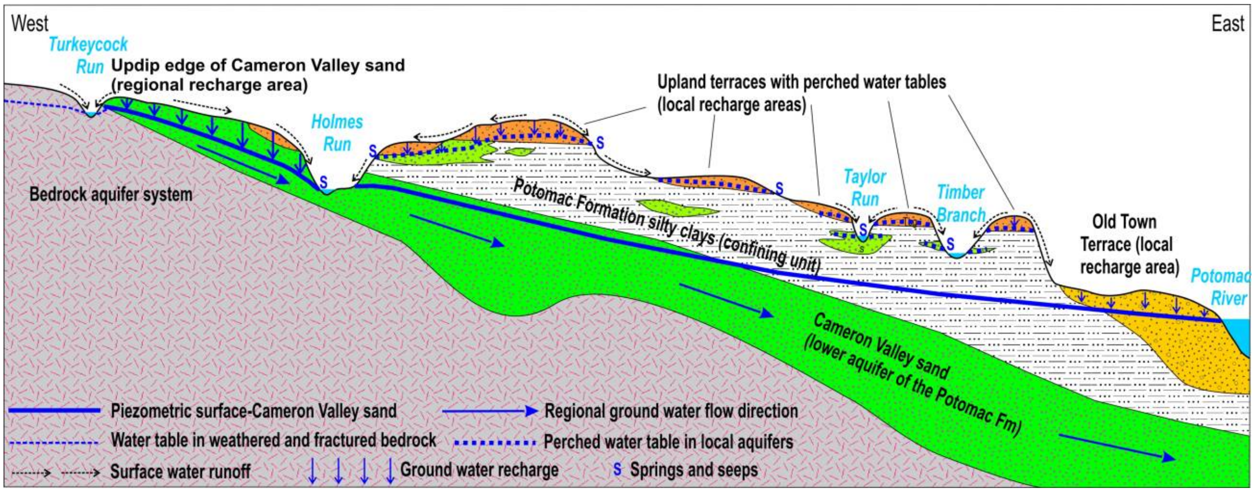


Figure 6-2. Simplified west-to-east cross section illustrating the main components of the hydrologic cycle in the city. The Cameron Valley sand is the major regional aquifer system; it receives direct recharge at its updip end in the western part of the map area, where it is exposed at the surface or covered by relatively permeable terraces and other surficial deposits. Further east, the aquifer system becomes increasingly confined by low-permeability silty clay units that inhibit recharge and generate large volumes of surface water runoff during storms. Regional ground water flow in the aquifer system is towards the Potomac River. The upland terraces and other sand bodies higher in the Potomac Formation comprise local aquifers, characterized by limited productivity and seasonally influenced water tables perched on the underlying silty clays. The Old Town terrace, on the other hand, is a potentially productive local aquifer; it contains an appreciable thickness of saturated sand and gravel that receives direct recharge from the terrace surface and is in direct contact with the Potomac River. Weathered and fractured bedrock constitutes a locally important aquifer in the far western part of the map area. Not to scale.

Strata capable of transmitting sufficient ground water to supply domestic wells occur along several different horizons, but none is more prolific than the Cameron Valley sand member, which makes up the lower 100-200 feet of the Potomac Formation beneath nearly the entire city. Also known as the "lower *aquifer*" of the Potomac Formation (e.g., **Froelich, 1985**; **Johnston, 1964**; **Mack, 1966**; **Johnston and Larson, 1977**; **Wilson and Fleck, 1990**), this mass of predominantly sandy sediment is one of the largest and most productive *aquifer systems* in the Washington, D.C. region. In addition to its role as a historical source of well water to numerous domestic and high-capacity users, the discharge from this aquifer system also is crucially important to the water budgets of most of the streams and ravines in the city, as well as to a number of other sites of environmental and ecological interest. In this atlas, the Cameron Valley sand is referred to as an "aquifer system", because it is composed of several individual sand bodies that each act as an aquifer, and which are locally separated, though not entirely isolated hydraulically, from one another by less permeable units of silt and clay, especially in the upper part of the system (figure 6-3).

Plate 6 depicts the *piezometric surface* of the Cameron Valley sand (figure 6-2), which represents the level to which ground water will rise in wells open to the aquifer system, and from which the direction of ground-water flow and its relationship to streams can be deduced. The map shows the locations of numerous seeps, springs, seepage swamps, and other places where ground water is discharging to the surface and/or interacting with surface water. Several other aspects of urban hydrology are also illustrated, among them the outfalls of filled ravines and the locations of historical wells that formerly supplied water for a variety of purposes.

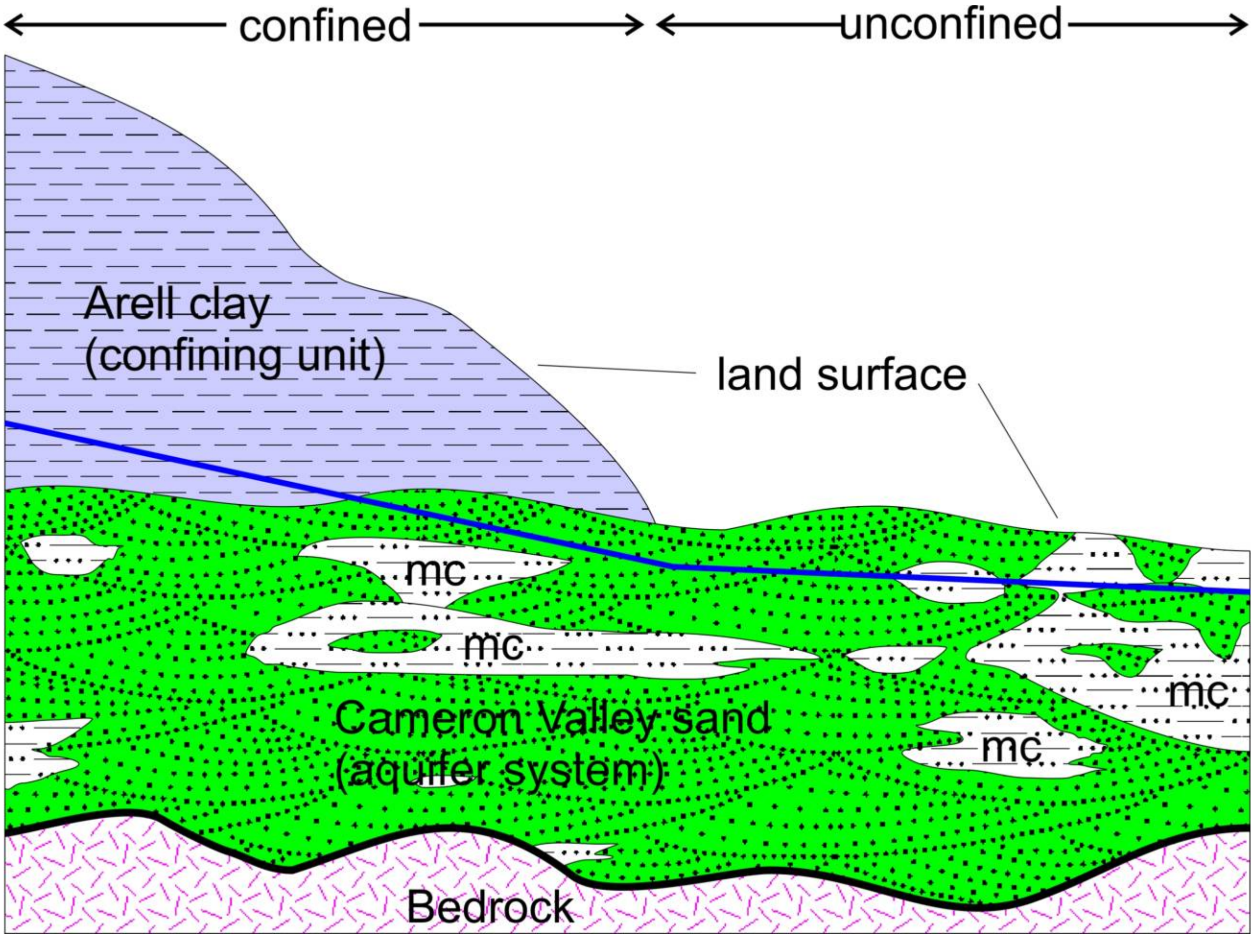


*Figure 6-3. Schematic diagram illustrating the concepts of aquifers, confining units, and aquifer systems, and the difference between confined and unconfined conditions. The Cameron Valley sand constitutes an aquifer system composed of permeable, water-bearing sand bodies (green)—some small, most quite large—separated locally by lenticular to irregular-shaped bodies of low-permeability clayey silt (mc). The silt bodies interrupt the continuity of the system by acting as local barriers to ground-water flow and may completely enclose some of the smaller sand aquifers. However, they do not disrupt the overall connectivity of the aquifer system, which behaves as a coherent hydraulic entity. On the left side of the diagram, the aquifer system is confined by the overlying Arell clay, whose low permeability inhibits recharge and acts as a low-flow barrier. This condition is typical of most of the Hospital escarpment and adjacent highlands. Artesian conditions are a subset of a confined aquifer and occur when water levels observed in wells (represented by the blue line) rise above the top of the aquifer system, as in the far left side. In contrast, the aquifer is unconfined in the right side of the diagram, because the top of the aquifer is at the land surface and is not capped by a low-permeability unit. This condition is widespread in the western part of the map area and in the Cameron Run Valley and adjacent areas; unconfined aquifers are commonly referred to as being under water-table conditions. Examples of all these conditions appear in the cross sections (**plate 2**).*

Previous Studies

Because it is the pre-eminent aquifer of the inner Coastal Plain, the lower part of the Potomac Formation has been the subject of a number of hydrogeologic studies in the greater DC area, many aimed at evaluating the water supply potential at specific sites in nearby parts of Maryland (e.g., **Andreasen, 1999**; **Andreasen and Mack, 1998**; **Mack, 1962**; **USACE, 1993**). Several studies of a more regional nature, however, all by the US Geological Survey (USGS), encompassed parts of northern Virginia, including Alexandria, and contain data that were incorporated into the present study. In his treatise on the ground water resources of the Washington area, **Johnston (1964)** compiled records for hundreds of old water wells, of which 80 are in the map area and included in the **water-well database** that accompanies **plate 1**. These records comprise a series of data tables (**Johnston, 1961**) composed of a variety of useful hydrogeological information, such as the depth, aquifer, and water level of each well. During the course of its Fairfax County mapping initiative during the 1970's, the USGS generated a wide range of information about the Potomac Formation. **Froelich (1985)** compiled much of this information into a format designed to aid in the interpretation of the regional *hydrogeology* of the *formation*. Among the many USGS studies compiled by Froelich (1985), a survey of historical water levels in the lower aquifer by **Johnston and Larson (1977)** is particularly valuable, because it compares water levels from two different times, using data obtained from many now-abandoned wells, and provides the only comprehensive analysis of the historically large withdrawals by *high-capacity wells*. Also included in the compilation is a study by **Froelich and others (1978)** that describes the hydrogeologic characteristics of the *Pleistocene alluvium* along the Potomac River, which includes the Old Town terrace of this atlas.

Data Sources and Methods

How the Map Was Made: The information presented on **plate 6** is based on a combination of hydrogeologic features and data directly observable in the modern landscape, as well as earlier geologic and historical observations concerning water resources. During the fieldwork for the atlas, particular attention was paid to recording the locations of visible ground-water discharge; such places include the banks of streams and ravines, as well as more isolated springs and seeps on uplands (figure 6-4). For purposes of mapping the *piezometric surface* of the Cameron Valley sand, outcrops with visible ground-water discharge provide a useful control on water-level elevations because they indicate that the aquifer system is saturated at that location and elevation. Nearly all of these seeping outcrops occur along the banks of

Figure 6-4. Left: Prominent seepage face in an outcrop of Cameron Valley sand along Holmes Run. The elevation of the water table in the seepage face is defined by the sharp change about halfway up the face from dry, bright orange-brown colors above to moist, dark greenish colors below. Photo by Tony Fleming. Right: The historic Federal Spring emerges at the base of a hillside along Russell Road. Photo by Rod Simmons.

the major streams and in perennial ravines, chiefly in the western part of the map area. Likewise, outcrops of sand that are not discharging ground water are also useful, since they indicate that the zone of saturation lies below the altitude of the exposure. The segments of streams exhibiting evidence of ground-water discharge from the Cameron Valley sand are shown on the plate.

Numerous *springs*, *seepage faces*, and *seepage swamps* associated with strata other than the Cameron Valley sand, as well as wetlands resulting from water perched on poorly-permeable sediment, were also observed in the city, and their locations are indicated on the plate. Finally, the approximate extents of several major historical wetlands (figure 6-5) on and adjacent to the Old Town terrace were determined from historical maps and records available in the city library and elsewhere, and by direct observation of the soils, hydrology, and vegetation present in these areas.

Figure 6-5. Four Mile Run estuary circa 1899, one of several major wetlands formerly present on and adjacent to the Old Town terrace. Photo credit: G.S. Miller, courtesy of the US Herbarium, Washington, D.C.

Water-Level Data: The Cameron Valley sand is by far the largest and most prolific aquifer system in the city, and for the most part, it is readily mappable by virtue of its stratigraphic position at the base of the Potomac Formation and atop the bedrock surface. The majority of all wells historically present in the city—and virtually every high-capacity well of any type—were developed in this aquifer system. Although most of the wells shown on plate 6 no longer exist, historical water-level measurements made in many of them are summarized by **Johnston (1961)** and **Johnston and Larson (1977)**, and provide a widely distributed source of water-level data. Although these water-level measurements date from decades ago, some as far back as the 1930's, they are nevertheless valuable for understanding the general configuration of water levels in the aquifer system, and the response of water levels to high-capacity pumping that occurred in the southeastern part of the map area prior to the mid 1970's. Additional water-level data collected within the past several years were available from several ground-water monitoring wells screened in the Cameron Valley sand, whose records are on file with the city. They are part of the **geotechnical boring data set** described in connection with **plate 1**.

Figure 6-6. Hydrogeology students measuring the water level in a ground-water monitoring well. Photo by Tony Fleming.

In addition to the wells, numerous geotechnical borings also terminated in the Cameron Valley sand. Some of the borings were uncased, which means that they were open (and potentially receiving water) from the entire interval between the ground surface and the bottom of the boring. Most were cased, however, which tends to restrict the inflow of water to a shorter interval near the bottom of the hole. The water levels reported on most of the boring records and shown on the plate were measured 24 hours (and in some cases, as much as one week) after the boring was completed; such "stabilized" water levels have largely equilibrated with their surroundings and represent some form of composite piezometric level.

Most of these geotechnical sites are under one of two types of hydrogeologic conditions that suggest that the water level observed in the borings will generally be representative of the actual piezometric surface: 1) the Cameron Valley sand is at the surface (or beneath thin surficial materials) and is, therefore, under water-table conditions; or 2) the Cameron Valley sand is overlain by Linconia silty clay or other poorly permeable strata that contribute a relatively smaller flow of water to the borehole; moreover, the Cameron Valley sand at the bottom of these borings is so much more permeable than the fine-grained units above it that it will essentially drain any excess water out of the borehole above and beyond the natural piezometric level of the sand, much like what happens during a slug test to measure *hydraulic conductivity*. For these reasons, the water levels reported from the geotechnical borings are judged to be relatively reliable, if not exact indicators of the actual water level in the Cameron Valley sand. Virtually all of these borings were made between 1990 and 2011, so they reflect relatively recent water-level conditions. The locations of all known historical water-supply wells, monitoring wells, and geotechnical borings open to the Cameron Valley sand are shown on **plate 6**, along with the reported water level.

Data Limitations: The piezometric contours were made using all of the aforementioned data. Considering that the water levels shown in the various wells and borings were measured over a wide span of time, and under a range of pumping conditions (e.g., a considerably deep *cone of depression* is known to have existed beneath the southeastern part of the map area up to the mid 1970's), the *piezometric contours* should be regarded not as absolute indicators of water levels at any specific point, but as a general guide to the configuration of hydraulic head in the aquifer system. Stated a bit differently, there is likely to be some variation between the mapped water level and what actually exists at any given point, but the overall shape of the contours is expected to be consistent with the actual shape of the piezometric surface. This assertion is based in part on two previous maps of the piezometric surface (**Johnston and Larsen, 1977**), which exhibited configurations similar to the present map. If anything, the present map may be more representative because, unlike the earlier ones, it takes into account the intersection of the aquifer system with surface waters into which the aquifer system is actively discharging, and which thus control the water levels and piezometric contours at those places. For the same reason, the contours are expected to more closely reflect the true water levels in the aquifer system in the western and southern parts of the map area, where the aquifer system is largely under water-table conditions and is extensively in contact with perennial streams.

On the other hand, in the southeastern part of the map area there may be greater divergence between the piezometric contours and actual water levels at any given well, for two main reasons. First, high-capacity wells that pumped large volumes of water from the aquifer up until the mid-1970's were concentrated in and just south of Old Town. The aquifer system below this area is documented to have been significantly dewatered by the early 1960's (see **Johnston and Larsen, 1977**, and **Froelich, 1985**), with water levels in some wells being drawn down as much as 300 feet below sea level, producing a deep, composite cone of depression beneath the southeastern part of the map area. Data presented by Johnston and Larsen (1977) indicate that considerable, but incomplete, recovery of water levels took place in parts of this area between 1960 and 1976; however, no systematic water-level measurements have been made since then, a task now rendered nearly impossible because most of the original wells used in these earlier measurements have been destroyed. It is tempting to speculate that water levels have returned substantially to their natural levels by projecting the recovery documented by Johnston and Larsen (1977) forward to the present — the sea level (0) piezometric contour shown on plate 6 is based on this idea—but the presence of ongoing large-scale pumping of the aquifer system across the river in Indian Head, Maryland and other places southeast of the map area casts doubt on such a conclusion. Therefore, the degree to which water levels have continued to rebound in the nearly 40 years since the work of Johnston and Larsen (1977) is ultimately unknown. **Plate 6** shows the approximate boundary of the area of depressed water levels shown by these authors as of 1976.

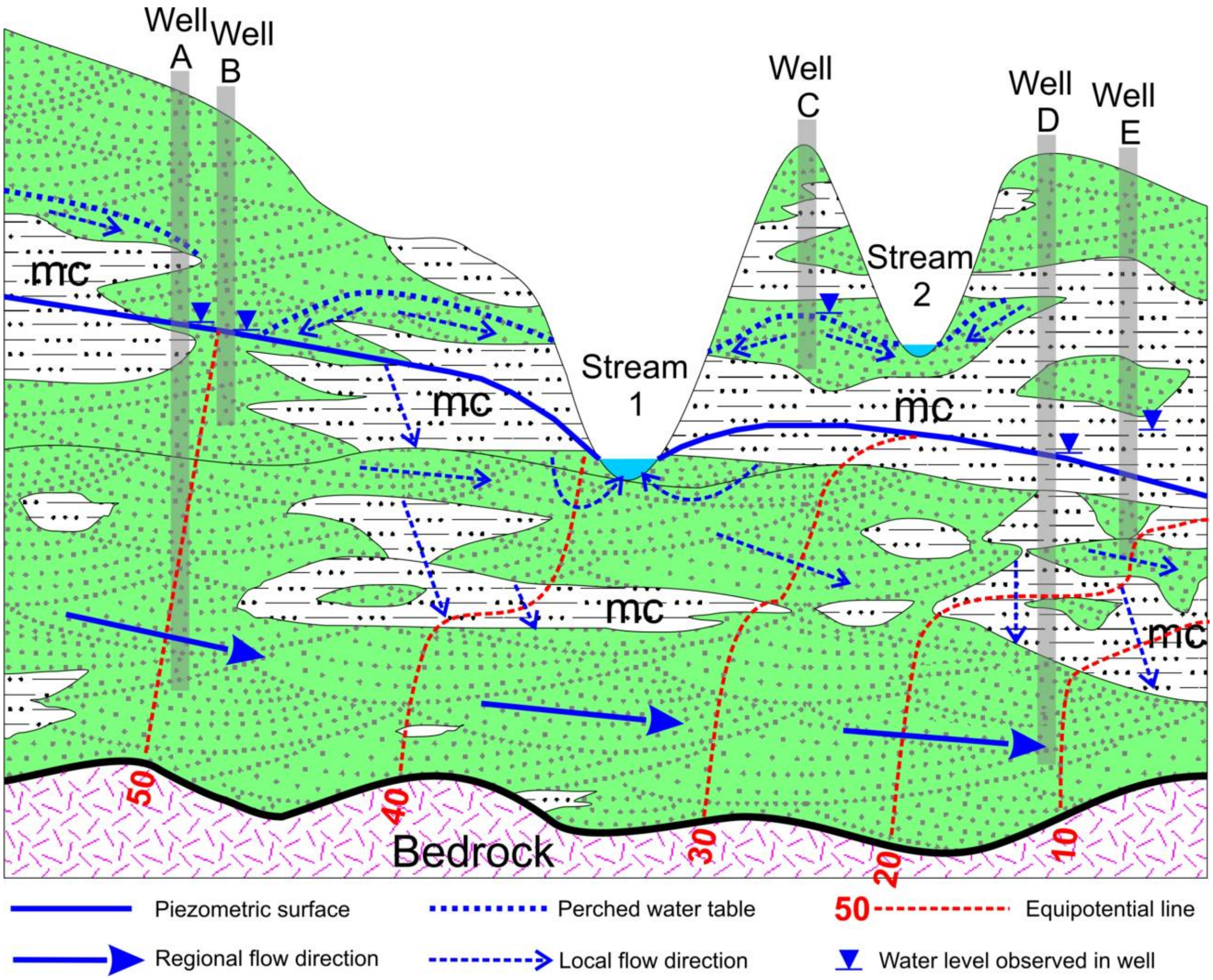


Figure 6-7. Schematic diagram illustrating the distribution of hydraulic head in relation to lithofacies geometry in the Cameron Valley sand. The lower part of the aquifer system is predominantly homogeneous sand (green) and is typified by horizontal hydraulic gradients, as illustrated by the schematic equipotential lines and regional ground-water flow arrows. Water levels observed in wells (A, B, D) screened in the lower part of the system are representative of the piezometric surface, as are the altitudes of streams (1) in contact with the lower part of the system. Well C and stream 2, on the other hand, are in a higher sand unit with a perched water table significantly higher than the piezometric surface, while well E is screened in a sand body enclosed in silt (mc) with strong vertical hydraulic gradients, resulting in a higher water level than nearby well D screened in the lower part of the system. The values assigned to the equipotential lines are arbitrary numbers designed to generally illustrate higher and lower hydraulic head in the aquifer system.

A second factor that may affect the reliability of water levels depicted in the eastern part of the map area is the nature of the aquifer system itself. In this atlas, the Cameron Valley sand is divided into two main units: 1) a relatively homogeneous lower unit composed almost entirely of sand (and minor gravel), and 2) a more heterogeneous upper unit that, while composed predominantly of sand bodies, also contains a significant number of lenses of silty clay, whose frequency appears to increase upward in the section. The largest known clay lenses are mapped separately on plates 4 and 6, but others likely remain undetected by current subsurface data. Such lenses are poorly permeable and, where relatively large, are expected to create vertical gradients in the aquifer system and potentially lead to the existence of one or more *perched water tables* at places (figure 6-7). Such places may include streams where ground-water discharge was observed, as well as wells screened in higher parts of the aquifer system. In either situation, a perched condition or downward vertical gradient would cause apparent water levels to be somewhat to considerably higher than the actual piezometric level at greater depth in the sandier part of the system. Stated differently, there is a greater possibility of strong vertical hydraulic gradients in the upper unit of the Cameron Valley sand, whereas lateral gradients are likely to predominate in the sandy lower unit.

Hydrogeology

General Observations: Alexandria is endowed with a bountiful supply of both surface water and ground water. A considerable volume of surface water flows into the city from other jurisdictions via the Potomac River and its major tributaries (Backlick, Holmes, Cameron, and Four Mile Runs); otherwise, all other water available in the city originates within the city. And, other than *surface runoff* following major storms, virtually all of that is ultimately derived from *ground water*. Most of the city occupies a major topographic high, where both ground water and surface water originate and flow outward towards the deeply entrenched valleys that form the city's boundaries. This constant flow of water is driven by large-scale differences in hydraulic head between the highlands, which occupy a piezometric mound and thus act as a regional ground-water recharge area, and the surrounding valleys, which form piezometric valleys and thus serve as regional ground-water discharge areas.

Surface Drainage: The central and western parts of the city are located on major topographic highs centered on Lincolnia and the Episcopal Seminary, which marks the city's highest elevations. This upland region could accurately be described as an incompletely dissected *plateau*, because it is characterized by concordant summit elevations and extensive, nearly flat upland areas that lack integrated surface drainage.

Figure 6-8. Most of the Seminary terrace is a level expanse (left) that is little changed by erosion since it was deposited. There is virtually no integrated surface drainage on the terrace, which typically terminates abruptly at the rim of the Hospital escarpment (right) and other sharp escarpments. Photos by Tony Fleming (left) and Rod Simmons (right).

The plateau surface consists of several step-like surfaces, each developed on a successively lower abandoned river terrace. The core of the highlands consists of the Seminary and Chinquapin Village terraces, which are the least dissected of the lot and lack any through-going surface drainages. The edges of the plateau are being actively incised by numerous short, straight ravines, some of which are poorly integrated with existing drainages. Most of these ravines are unnamed—in fact, there are only three major, formally named tributary ravines in the uplands of the city: Lucky Run, Timber Branch-Hoeff Run, and Taylor Run. Other sizable drainages include the unnamed streams that flow through Rynex natural area (referred to here as "Rynex ravine"), Fort Williams Park (informally known as "Strawberry run"), and Winkler Nature Preserve ("Winkler run"). Most of the ravines in the city are rapidly downcutting in response to *Pleistocene* glaciation, which repeatedly lowered sea level by hundreds of feet and caused the large trunk streams that bound the city to cut deep *Ice Age* valleys. The smaller tributary ravines are now adjusting as they attempt to equalize their gradients relative to the much larger streams they flow into. This process is being artificially accelerated during major precipitation events by the large volume of *urban stormwater runoff* that enters most of these headwaters streams (figure 6-8).

Figure 6-8. The headwaters of most tributary ravines in the City are greatly altered by urbanization, and most emerge from outfalls rather than natural springs, which are now buried or otherwise obscured. The stream in Rynex natural area (left) has two different buried segments, each of which emerges from an outfall. The most extremely altered large tributary stream in the City is Lucky Run, virtually the entire headwaters of which are buried above its outfall and brief aboveground appearance in Stonegate Scenic Easement (right). The hydrology of these headwaters streams is often very unnatural, exhibiting extreme swings in discharge during precipitation events, when massive volumes of urban stormwater converge on the outfalls. The result is unnaturally deep, gully-like channel profiles with a strong propensity towards flash floods. Photos by Tony Fleming.

Widespread urbanization of the watersheds of Four Mile and Cameron Runs during the 20th century, coupled with ill-advised development in floodplains, led to increased flood peaks and repeated damage to infrastructure along all of the trunk streams. This situation ultimately led to a series of major flood-control projects that permanently altered both the form, hydrology, and in some cases, the locations of the master streams (figure 6-9). Major segments of Holmes, Backlick, Four Mile, and Cameron Runs were straightened, channelized, armored, and otherwise modified to convey floodwaters more quickly through the city. The reach of Holmes Run adjacent to Beatley Library, for example, was relocated northward—it formerly flowed through the library grounds in a channel still visible as a low swale—while the section of Backlick Run adjacent to Cameron Station Military Reservation (now Ben Brenman Park) was replaced with a concrete flume. Despite these alterations, Holmes Run is still relatively natural in many places and has the most original channel remaining of the 4 master streams. The Cameron Run Valley, on the other hand, is perhaps the most intensely altered geologic terrain in the City, and the stream channel today bears almost no resemblance to its pre-urban course and appearance, and little relation to the distributions of terraces and major bodies of modern alluvium (see **plate 5**).

Figure 6-9. A) the section of Holmes Run east of Brenman Park was straightened in the 1970's, but remains more or less in its original location; B) the upper section of Holmes Run flows in a bedrock-walled channel and is little altered from its pre-settlement state; C) the flumed section of Backlick Run at Brenman Park. Such alterations commonly lead to an escalating series of remedial actions: here, the rip rap had to be added to stabilize the streambank where the stream debouches from the flume; D) nearly all of Cameron Run occupies an artificial channel walled by rip rap, with no connectivity to a floodplain to store water during large floods. The artificial channel does not follow the original course of the stream (E), which is still visible as a low, wet swale in a few places. Lake Cook also occupies a section of the original channel; F) the Cameron Run millrace circa 1889. Note the expansive, open floodplain. Photo B by Rod Simmons, Photo F from Alexandria Library, all others by Tony Fleming.

Ground water plays a major role in the water budget of every perennial stream in the City. Even the smaller ravines and streams that originate in the City, including intermittent streams, receive at least seasonal ground-water discharge. It is not coincidental that the headwaters of virtually all of the city's ravines are found at the edges of the upland terraces. As detailed below, these locations are ideal for the development of the springs and seeps that feed these drainages. Although all of the surface drainages in the city can and do carry large volumes of urban storm-water runoff, this typically occurs for only a relatively short period following major storms. The rest of the time, base flow in these drainages is comprised of ground water discharge. This is also true for the major streams that bound the city. Cameron, Backlick, Holmes, and Four Mile Runs occupy regional ground-water discharge areas, and large volumes of ground water are constantly discharging into them along the edges of the city. The Potomac River is the master stream and ground-water discharge area. Not only does all surface drainage from the city end up in the river, but a substantial amount of ground water also discharges to the river from the Old Town terrace, which is composed chiefly of sand and gravel and fronts the river for several miles.

Ground Water Recharge and Terrace Hydrology: While ground-water recharge undoubtedly occurs in a variety of geologic settings in the city, two settings in particular probably account for the vast majority of recharge that reaches the city's main aquifers. One of these encompasses places where the Cameron Valley sand crops out at the surface at the updip end of the Potomac Formation, and receives direct infiltration of precipitation (figure 6-2). This setting is indicated in a general way by the distribution of map units on **plate 6**, and more specifically by the coincidence of piezometric highs in the western part of the map area with the Cameron Valley sand outcrop. Large portions of this updip area are covered by some of the upland terraces, which comprise the second major setting for ground-water recharge and, as discussed below, may enhance recharge to underlying aquifers.

Extensive areas of the upland terraces that cap the Alexandria highlands lack significant surface drainage. These terraces are frequently typified by flat to very slight surface gradients that tend to cause precipitation to pond on the surface (figure 6-10) instead of rapidly running off overland. Some parts of the terrace surfaces exhibit sag-and-swell microtopography, which is even more effective in trapping runoff. Relatively permeable gravel at shallow depth beneath the terrace surfaces favors ground-water recharge. Although it is much lower in the landscape, the same characteristics apply to the Old Town terrace, which underlies a substantial portion of the eastern part of the city.

Figure 6-10. Level, undissected terrace surfaces are favorable places for ground-water recharge because they promote ponding of water, evidenced by the dark patches in the ballfield at Stevenson Park (left) and standing water following a storm (right) at Forest Park (right). Photos by Tony Fleming (left) and Rod Simmons (right).

Parts of the terraces overlie fine-grained members of the Potomac Formation, such as the Arell clay and Lincolnia silty clay, which are significantly less permeable than the terrace gravel. The permeability contrast commonly leads to a perched water table in the gravel (figure 6-11). During major recharge events, such as prolonged rainy periods, one or more ground-water mounds are likely to develop in the gravel, and water will flow laterally away from these toward the edges of the terraces. Hydraulic gradients, however, are likely to be slight due to the relatively level nature of the terraces. Local ground-water flow direction at any given place in the terrace gravels is likely to be highly site specific and will be controlled by local irregularities in the base of the gravel, such as places where the terrace gravels are channeled into the underlying Potomac Formation. Such channels are likely to be significant conduits for ground-water flow under the terraces, and even a difference of a few feet in relief along the base of the terrace may make a large difference in the direction and rate of ground-water flow. Such features are also likely to be important places for the initiation of landslides along the edges of the terraces (**Obermeier, 1984**).

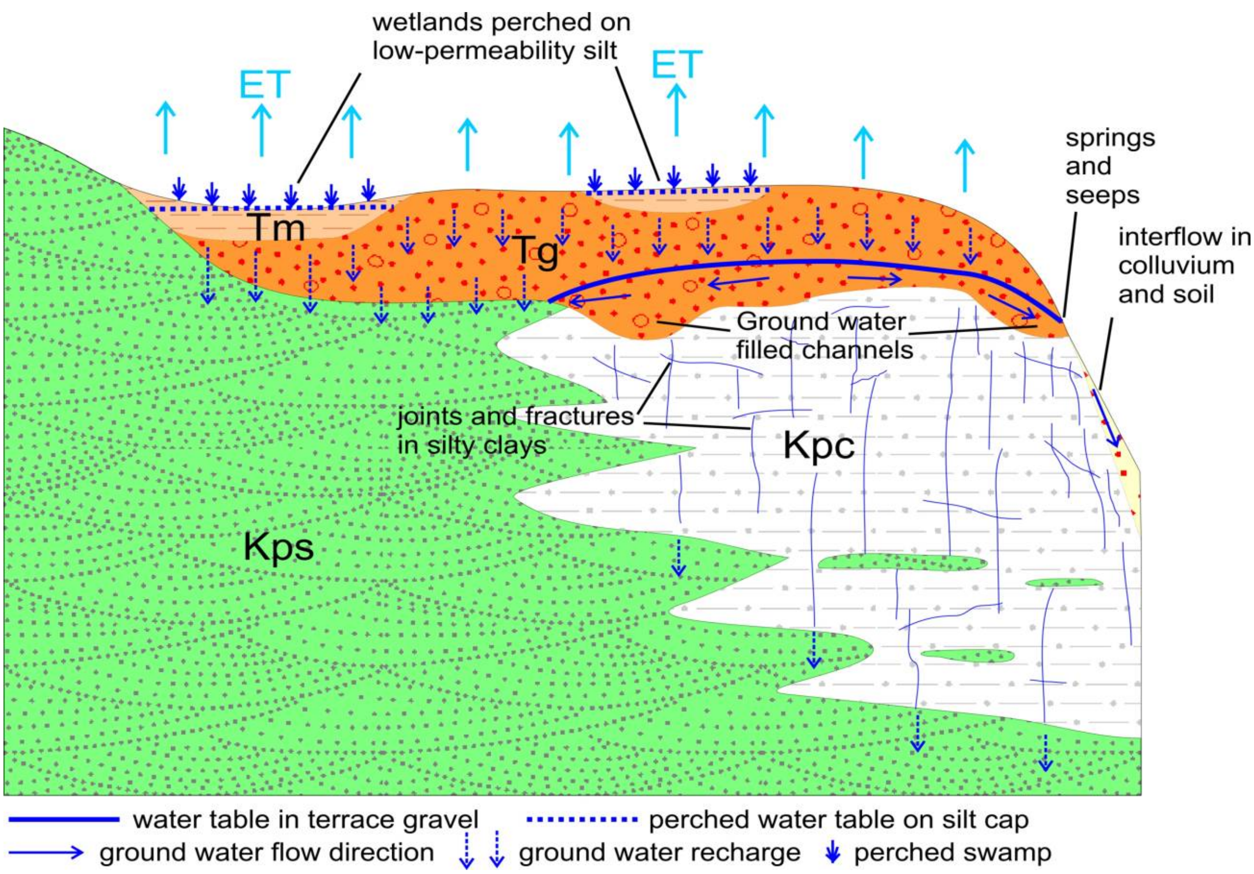


Figure 6-11. Hydrologic cycle on upland terraces. Precipitation that falls directly on gravel (Tg) readily infiltrates the terraces and moves downward as recharge, whereas precipitation that falls on the poorly-permeable silt caps (Tm) tends to form swamps and other ponded areas. Some of the precipitation in both places returns to the atmosphere as evapotranspiration (ET). Following periods of major recharge, a water table typically forms beneath parts of the terrace floored by the much less permeable silty clays of the Potomac Formation (Kpc). A small portion of ground water moves down through the silty clay via fractures, joints, and small sand seams, but most flows laterally along the top of the silty clay until it reaches the edge of the terrace and discharges in springs, or encounters more permeable sands (Kps) and migrates downward to recharge lower aquifers in the Potomac Formation or bedrock. The water table below the terrace is often seasonal and may disappear entirely during dry periods. Channels at the base of the terrace are major conduits for ground water flow. The left side of the diagram is typical of terraces that overlie the updip part of the Cameron Valley sand in the western part of the map area, whereas the right side is characteristic of most terraces elsewhere.

Several possible flow paths await ground water that recharges through the terraces. A portion of it flows laterally along the top of the underlying Potomac Formation until it reaches the edges of the terraces, where it discharges in *springs* and diffuse *seeps* localized along the contact of the terrace gravel and fine-grained sediments in the underlying Potomac Formation. Concave sections of the slopes bordering the terraces are favorable for spring development, because they act like a bowl, "focusing" the flow of shallow ground water inward toward the central, lowest point. The heads of ravines exemplify the concept of ground-water focusing in concave hillsides: many springs in the city emerge at the heads of ravines and furnish the base flow that keeps the ravines moist. The opposite is also true: convex hillsides tend to spread out the flow of shallow ground water, and make it less likely that it will emerge in those locations.

Not all of the ground water that discharges along the edges of terraces does so as visible, discrete springs and seeps. Some of it is removed by *evapotranspiration* during the growing season. Some of it also continues downslope as *interflow*—moisture that moves through the relatively permeable mantle of colluvium and soil close to the surface. The phenomenon of interflow is most readily observable from one to several days following a major soaking rain: precipitation that infiltrated near the top of the slope moves downslope, parallel to and just beneath the soil surface, and eventually seeps out near the base. This phenomenon is largely responsible for producing the moist, favorable growing conditions characteristic of many toeslopes.

Depending on the thickness of the terrace gravel, the amount of open land available for ground-water recharge, and other factors, the water table beneath any given part of a terrace (and the springs and seeps that emerge from it) may be either perennial or ephemeral. The largest perennial springs are typically found where the heads of the deepest ravines coincide with channels in the bases of the terrace gravel, or with large colluvial fans that derive and store water from the adjacent terrace gravel. Good examples are visible in the wooded ravine on the west side of St. Stephens School, and in the heads of the twin ravines in Clermont Woods Park in Fairfax County. The edges of all of the upland terraces are also popular places for development, however, because of the level terrain and expansive views they typically offer, and most of the original springs that once existed in this setting have been destroyed or obscured by urbanization. Typically, the "headwaters" of most of these ravines now emerge from outfalls.

Figure 6-12. Ground water issues to the surface both as distinct springs (left) with a visible orifice, and as more diffuse seepage faces (right) commonly flanking streams. Both types of seepage are often marked by tell-tale hydrophytic vegetation composed of obligate seepage plants, such as skunk cabbage, sweetbay magnolia, and several others. See the ***Ecological Significance of Ground Water*** *later in this explanation. Photos by Tony Fleming.*

Some of the precipitation that falls on the terraces stays on their surfaces. Parts of these terraces are swamps perched on weathered, low-permeability silt and clay that caps the terraces. One of the largest examples is the extensive swampy area along both sides of Quaker Lane south of King Street, encompassing the northeast corner of the Episcopal Seminary as well as portions of Chinquapin Village and Chapel Hill. Water frequently ponds in slight depressions and swales on this landscape, which is underlain at places by upwards of ten feet of clayey, poorly permeable silt. The silt hugs the inboard edge of the terrace, lying in a distinct band near the base of the scarp that separates this terrace from the higher Seminary terrace. Numerous large specimens of pin oak, sweet gum, red maple, and other *hydrophytic* plants attest to the saturated conditions on this section of the terrace landscape. The hydrology of these swamps is probably complex, featuring a considerable amount of interaction between surface water and shallow ground water, with ground water slowly seeping out of one side of a swale or depression, and back into the other. There are typically no surface streams in this landscape.

Figure 6-13. Upper left-Upland depressional swamp perched on Dowden terrace. Despite standing 100 feet above local base level, the forest at this site consists of hydrophytic trees more typical of bottomlands along major streams, attesting to how effectively the low-permeability silt cap on the terrace retains water. Above right-small pool in a swale on the Chinquapin Village terrace. The silt (left) has experienced a complicated weathering history and contains appreciable clay, but lacks secondary openings such as joints and fractures that would otherwise promote subsoil drainage. As a result, the soil profile is typically gleyed, yet also exhibits a strongly developed fragipan—a nearly impervious subsoil horizon with a prismatic structure that contributes to strong seasonal wetting and drying cycles. Evapotranspiration is the main way water is removed from these poorly drained areas. Photos by Rod Simmons.

Not all of the water that infiltrates into the terraces comes out as lateral discharge. Some of it migrates vertically downward into the underlying Potomac Formation where the latter consists of sandy or mixed units, such as the Cameron Valley and Winkler sands, and parts of the Chinquapin Hollow member. This condition is especially prevalent in the far western and the northeastern parts of the highlands, where the Cameron Valley sand and

Chinquapin Hollow member respectively form the surface of the Potomac Formation over wide areas, and to a lesser extent along the Winkler outcrop belt near Shirley Highway. The permeabilities of these units are moderate to high—comparable at places to the terrace gravel—so any permeability contrast between the terrace gravel and the underlying sediment is relatively small. In these places, there is likely to be little ground water perched in the terrace gravel, and much of the recharge that occurs on the terraces continues to move vertically downward into subjacent aquifers. It seems probable, for example, that the Cameron Valley sand receives abundant ground-water recharge just west of the city limits, especially in the Baileys Crossroads and Lincolnia Heights areas, where its feather edge subcrops directly beneath gravel of the Dowden terrace.

On the other hand, large parts of the terraces are floored by fine-grained members of the Potomac Formation, such as the Arell clay and Lincolnia silty clay, but even these relatively poorly permeable sediments are capable of transmitting some ground water through networks of interconnected fractures and small sand bodies. To the best of my knowledge, no one has ever attempted to quantify how much ground water leaks through these *confining units* in northern Virginia, but the piezometric high that exists in the underlying Cameron Valley sand beneath some of these clayey sediments in the western half of the city is substantial, and indicates that appreciable recharge may be occurring through these units. One possible analogue is the fractured, clay-rich glacial tills of the glaciated Midwest, which have been shown to transmit between 2 and 6 inches per year of water into underlying aquifers (c.f., **Stephenson and others, 1988**). This is probably a reasonable estimate of the amount of vertical leakage through thick sections of Arell clay and similarly tight confining units that cap the Cameron Valley sand in Alexandria and vicinity.

In summary, the Alexandria highlands (along with adjacent parts of Fairfax County) appear to constitute a regional ground-water recharge area, with much of that recharge occurring on the flat, poorly drained landscapes of the upland terraces.

Significance of the Cameron Valley Sand Aquifer System: Aquifers occur at a variety of horizons in Alexandria. These include fractured and weathered *bedrock*, sands at various positions in the *Potomac Formation*, the upland terrace gravels, and the Old Town terrace. Johnston (**1961**; **1964**) documented wells developed in all of these units within the city (figure 6-14). As noted above, the terrace gravels commonly contain a perched water table; based on water level data from Johnston (1961), it appears that the terrace gravels are rarely saturated to more than 5 or 6 feet above their bases. As aquifers, the terrace gravels are suited only to shallow, low-capacity domestic wells. Before the advent of widespread public water supply systems, many residences on the terraces obtained water from large-diameter dug wells, which seldom yielded more than a few gallons per minute (gpm) and were subject to frequent water-level declines and outright failures during droughts. The crystalline bedrock was also utilized as a source of water for domestic wells, as well as for a few installations requiring greater capacity. Typically, the bedrock yields appreciable water only where a well intersects several interconnected, open *joints*. Typical bedrock well yields reported by Johnston (1961, 1964) for northern Virginia are less than 10 gpm, with a few very deep and/or large-diameter wells capable of yielding up to 100 gpm. Some dug wells were also developed in the mantle of weathered residuum, known as *saprolite*, that commonly overlies the fresh, unweathered bedrock on uplands. Like the terrace gravels, the saprolite typically produces low-yielding wells.

Figure 6-14. Examples of different kinds of wells. The top two photos are 36" diameter bored wells, commonly used for residential supplies on the upland terraces. These wells typically utilize a concrete or brick lining and are seldom more than about 30 feet deep. Their shallowness makes them susceptible to both drought and bacterial contamination. Dowden terrace has by far the most such wells in the map area, probably because it is the thickest and most aerially extensive terrace gravel, and thus provides a more reliable water supply than the others. The lower left photo is a typical 4" drilled well with a steel casing. This is another common configuration for residential and smaller commercial applications. The lower right photo shows a 10" drilled well. This size of well is commonly used for high-capacity industrial, commercial, or public water supply applications. Dozens of deep wells similar to this were drilled into the Cameron Valley sand in the Old Town area and were widely used until approximately the mid 1970's. Only a few remain in use today. Upper photos by Rod Simmons, lower photos by Tony Fleming.

Sand bodies capable of yielding water adequate for typical domestic needs occur at several horizons in the Potomac Formation; however, none are as reliable and productive as the Cameron Valley sand at the base of the formation. This large mass of predominantly sandy sediment contains the only aquifers in the City proven to consistently yield large quantities of water to high-capacity wells (defined as >= 100,000 gallons per day). Large-diameter wells historically developed in this aquifer system in and near Alexandria commonly yielded more than 250 gpm, and a few yielded between 500 and 1,000 gpm, according to **Johnston (1961)**. This productivity is easily understood in terms of the geology: the Cameron Valley sand nearly everywhere contains 50-100 feet of sand at its base, and at some places in the Cameron and Four Mile Run bedrock valleys, the upper part of the unit also consists almost entirely of sand, resulting in composite sections of sand on the order of 150 to (exceptionally) 200 feet thick at the base of the Potomac Formation. Such thicknesses of permeable material are not known to be replicated anywhere else in this part of northern Virginia. On the other hand, productivity is limited by the presence of silty clay lenses at various places in the unit, especially in the upper part, and by deep weathering that has transformed much of the original *feldspar* in these *arkosic* sands to clay, thereby reducing the yield of the aquifer system from what it would be in an unweathered state. Nevertheless, it is not surprising that high-capacity wells developed in the Cameron Valley sand played an important role in the city's past industrial legacy.

Piezometric Surface and Ground-Water Flow Patterns: The *piezometric surface* shown in **plate 6** reveals the overall distribution of water levels in the Cameron Valley aquifer system, from which the direction of ground-water flow and its relationship to streams can be deduced. As noted earlier, the piezometric surface is defined by the level to which ground water will rise in a well open to the aquifer system. Another way of stating this is that the piezometric surface represents the distribution of *hydraulic potential energy* (which itself is a combination of elevation and pressure head) in the aquifer system. At some places (indicated by the green color on plate 6), the aquifer system is unconfined, which means that it is not capped by poorly-permeable confining units. In these places, the aquifer system is under water-table conditions (figure 6-3), and the piezometric surface simply represents the elevation of the *water table*, which is at atmospheric pressure.

At other places, such as along Seminary Road, the Cameron Valley sand is capped by moderate to thick sequences of clayey sediment that impede the movement of water into and out of the aquifer system. Over parts of the capped area, water levels in the aquifer system stand higher than the top of the aquifer system (and above the base of the confining unit), resulting in a truly confined, or *artesian*, condition in which hydrostatic pressure in the aquifer system is greater than atmospheric pressure. In other words, the entire thickness of the aquifer system is saturated. At other places, however, especially in the western portions of the map area, the aquifer system is technically not under artesian conditions because water levels do not rise to the base of the confining unit. In such places, the aquifer system is more or less still under water table conditions, and is more accurately referred to as being "capped" or "semi-confined" by fine-grained sediment, as opposed to "confined" or "artesian". Regardless of these differences, ground-water flow is always perpendicular to the contours at any given place in the flow system.

The configuration of the piezometric contours on plate 6 clearly shows that regional ground-water flow in the Cameron Valley sand is east-southeast towards the Potomac River, with many local variations around the larger streams. The major recharge areas are inferred to coincide with the highest parts of the piezometric surface in the far western parts of the city and adjacent areas in Fairfax County. For the most part, the inferred recharge areas correspond to the subcrop of the aquifer system along the eroded surface of the Potomac Formation (see **plate 4**) beneath the Dowden terrace (see **plate 5**), but piezometric highs continue eastward beneath parts of the landscape where the aquifer system is capped by the Lincolnia silty clay and younger units, indicating that there may be appreciable leakage through these overlying units into the aquifer system in that area.

The piezometric contours deflect sharply around major and intermediate streams, especially where these streams are entrenched into the aquifer system, indicating that the streams exert a strong influence on local water levels and direction of ground-water flow. The configuration of the contours indicates that the local ground-water flow direction is perpendicular to, or obliquely downstream towards any stream in direct contact with the aquifer system. All of these streams act as *ground-water discharge areas*, and are fed by ground water that recharged on the piezometric highs on the uplands. Most of the perennial streams in Alexandria are known as "gaining streams" because their volume increases downstream in response to the ongoing discharge of ground-water along their beds and banks. This is especially true of Four Mile and Holmes Runs, whose discharges increase markedly as they flow through the city. These two streams are deeply entrenched into the heart of the Cameron Valley sand, from which they receive a large volume of ground-water discharge along their courses through the City.

The Old Town Terrace: A Major Ground-Water Resource?

The Old Town terrace is the surface expression of a large body of sandy, late Pleistocene alluvium that extends to depths as great as 125 feet below the surface of the terrace. It is related to a series of deposits of the ancestral Potomac River that extend southward from Washington, D.C. to Mason Neck in southeastern Fairfax County and beyond (**Froelich and others, 1978**). The large abandoned meander represented by Hybla Valley is another prominent local landform related to these late Pleistocene river deposits.

Dozens of historical wells and geotechnical borings that penetrate the Old Town terrace indicate that the underlying deposits contain a substantial thickness of saturated sand and gravel (figure 6-15). Unlike the Potomac Formation and upland terraces, however, the Old Town terrace has not experienced millions of years of intense weathering, consequently the sandy units beneath its surface contain much less silt and clay produced by weathering of feldspar and other susceptible minerals (see table 5-4 in the **expanded explanation of plate 5**). This means the spaces between the sand grains are likely to be larger and less plugged up by mud, resulting in higher *hydraulic conductivities*, and potentially greater yields per foot of saturated aquifer thickness.

Unfortunately, evidence bearing directly on the hydraulic properties of the Old Town terrace is lacking: although numerous wells were historically present on the terrace, all of them were completed in the underlying Potomac Formation. Not a single record is known for any well completed in the terrace alluvium, so there is not even anecdotal evidence for what the formation might yield to a large-diameter well. Despite the lack of historical ground-water withdrawals, several lines of indirect evidence suggest that the terrace hosts a significant ground-water resource that potentially rivals that in the underlying Cameron Valley sand.

In addition to their relatively clean texture, sand and gravel units below sizable parts of the terrace are more than 50 feet thick and locally attain thicknesses greater than 100 feet. The largest reported thicknesses mostly lie beneath Old Town in a belt extending southeast from approximately Bashford Lane to the waterfront. The central part of this belt also coincides with the largest bodies of gravel known from current borings (figure 6-15), which appear to fill a channel, or former thalweg, of the ancestral Potomac River. The trend of this feature is ill-defined—large parts of the terrace lack borings of sufficient depth to trace it—but it almost certainly extends beneath other parts of the terrace and waterfront. In any case, sections of coarse, clean sand and gravel 50 to 100 feet thick are expected to have high *transmissivities*, with well yields potentially on the order of 500 - 1,000 gallons per minute.

The terrace deposits have the added advantage of being unconfined—they are at the land surface and are under water-table conditions—and therefore receive direct recharge over most or all of their extent beneath the terrace. This same property also makes them more susceptible to contamination from surface sources, however. Finally, the geologic setting suggests that the thick sand and gravel deposits below the terrace are potentially in direct hydraulic contact with the Potomac River near the waterfront. Induced riverbank infiltration is the term used to describe the practice of using wells to induce ground-water recharge from an adjacent stream, which in the case of the adjacent Potomac estuary represents an almost inexhaustible supply of water. Thus, while the geologic setting of the terrace points toward a productive ground-water resource, it must be emphasized that the data are incomplete and the resource unproven; considerably more subsurface mapping and analysis are needed, along with a test drilling program, to better quantify the potential yield and ambient water quality of this seemingly large aquifer.

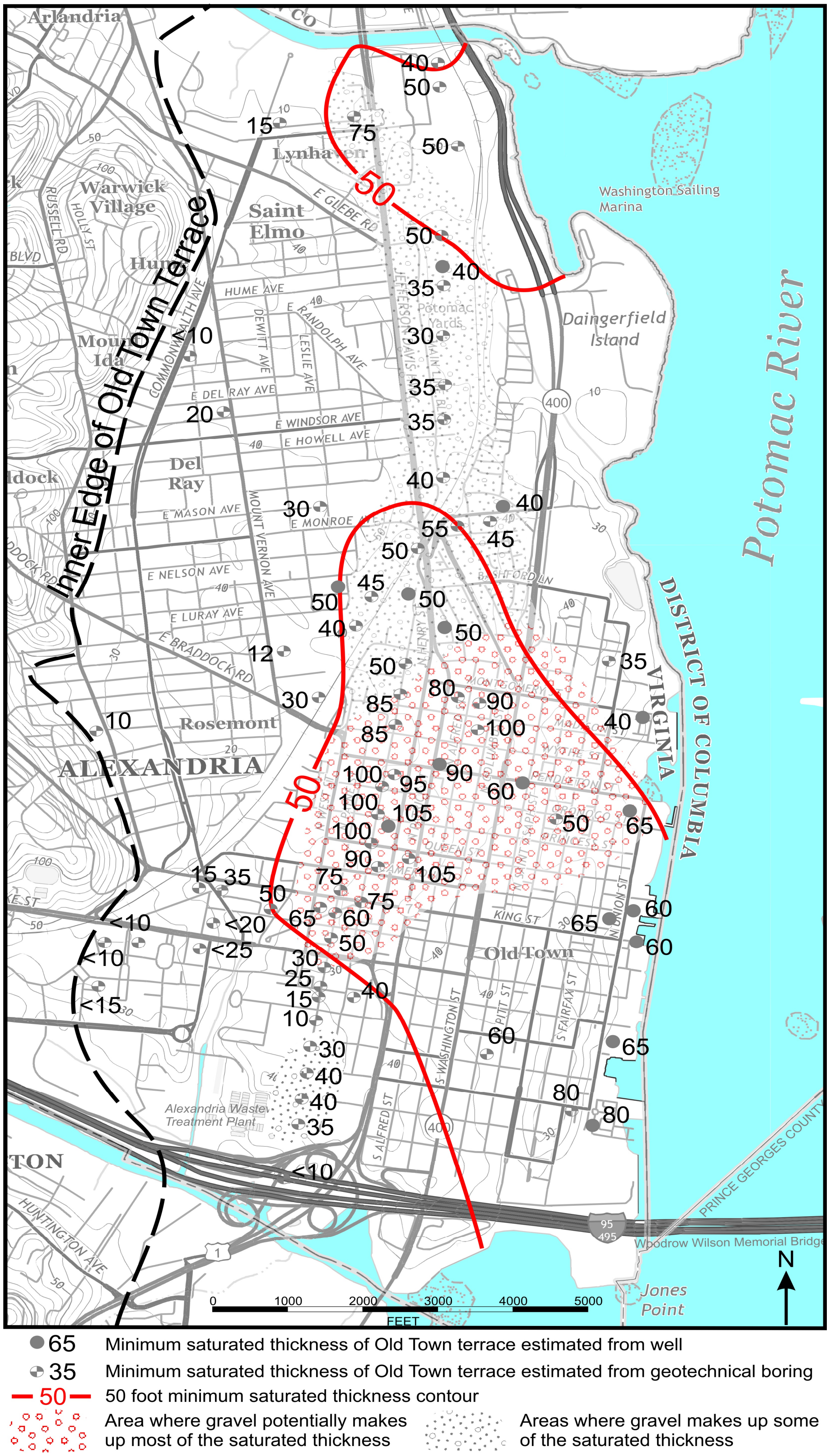


Figure 6-15. The Old Town terrace is the single most extensive landform in the City of Alexandria, covering more than a quarter of the land area in the city. At many places, the sequence of alluvial deposits below the terrace surface contains thick granular sediment – mainly medium to coarse sand with major intervals of gravel in some locations. Available data indicate that an appreciable thickness of the sand and gravel is saturated. Many of the geotechnical borings on the terrace do not penetrate the full thickness of the underlying alluvium, hence the values shown on the figure are estimates of the minimum saturated thickness of the water-bearing alluvium, based in part on interpretations of the cross sections in this area. Moderate to thick zones of gravel are reported in some borings, notably in the north-central part of Old Town, where a deep, gravel-filled channel appears to be present. Due to the uneven distribution of deep borehole data, the trend of this channel is not well established at this time, but it appears to represent a former thalweg of the ancestral Potomac River, and presumably extends beneath other parts of the terrace to the north and south. Cross sections ***2A***, ***2B***, ***2C***, *and* ***2F*** *illustrate the subsurface geology below this part of the terrace.*

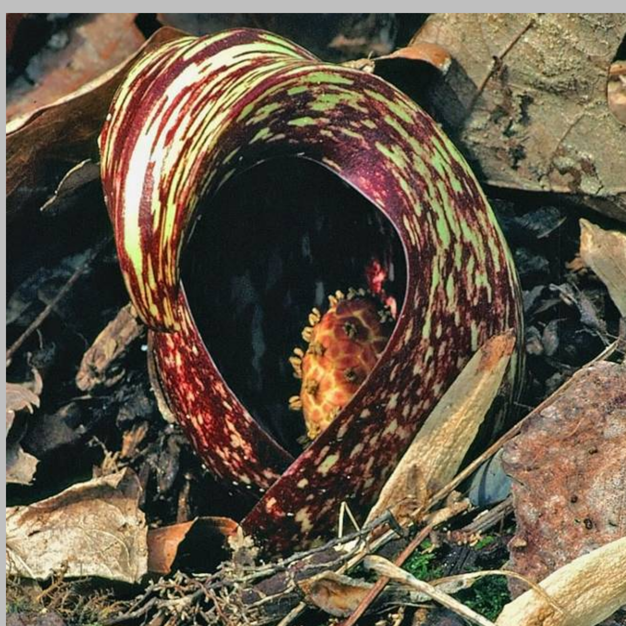
Ecological Significance of Ground Water: Ground water plays a crucial role at several important natural areas in the city and surrounding areas (see text box below, ***Obligate Seepage Plants and Ground Water Dependent Ecosystems***). Many of these areas are situated along ravines and, as noted previously, every perennial ravine in the city is ultimately fed by ground water. By definition, *seepage swamps* are forested wetlands located where ground water discharges, most commonly from the Potomac Formation. Most of these swamps are moderately acidic, with such acid-loving species as sphagnum moss, poison sumac, and sweetbay magnolia reflecting relatively low levels of calcium and other bases in the ground water and a generally nutrient-poor condition.

Figure 6-16. The seepage swamp at Barcroft Park in Arlington County hosts the region's largest outpost of sweetbay magnolia. Photo by Rod Simmons.

The best example is the large magnolia swamp along Four Mile Run at Barcroft Park in southern Arlington County (figure 6-16), which is characterized by ground-water discharge of hundreds of gallons per minute from the Cameron Valley sand (**Fleming, 2005**; **2010**), but there are several smaller examples in the city (**Simmons, 2015**). The magnolia swamps in two unnamed ravines in Dora Kelley Park, and another similar swamp in Rynex, are also fed by ground-water discharge from sandy and gravelly units near the base of the Cameron Valley sand. The seepage swamp in Chinquapin Hollow, on the other hand, appears to receive ground water from a colluvial *fan*, but it is more likely that gravel of the Chinquapin Village terrace or a sandy unit of the Chinquapin Hollow member of the Potomac Formation is the true source, concealed beneath a mantle of gravelly hillside sediment.

Obligate Seepage Plants and Ground-Water Dependent Ecosystems

Certain plant species in Alexandria and elsewhere along the mid-Atlantic Fall Zone are found only in places where ground water is actively discharging to the surface. These obligate seepage plants form distinctive ground-water dependent ecosystems that, as the name implies, are exquisitely dependent on the physical, chemical, and/or thermal characteristics of springs and seeps, and are found in no other geologic environment in the region. Some of the more iconic and readily recognizable members of this group of plants include sphagnum moss, poison sumac, sweetbay magnolia, and skunk cabbage.



Above left-Sphagnum moss is regionally restricted to ground-water fed wetlands, though elsewhere it occurs in a variety of wetlands. Photo by Rod Simmons. Above right-Poison sumac by Gary P. Fleming. Left-Skunk cabbage is among the most unusual of these obligate seepage plants from an evolutionary perspective. Unlike most plants, skunk cabbage flowers in late winter—sometimes when there is still snow on the ground—a feat made possible by its hooded flowering organ, a highly specialized physiological adaptation that allows the plant to capture the latent heat of ground water, whose temperature is near 55° F year round. Skunk cabbage also has an extraordinarily fast respiration rate—twice that of most plants—which represents another source of heat. Photo by Gary P. Fleming.

A sometimes confusing variety of names have been applied to these seepage wetlands—"seepage swamps", "bogs", and "poor fens", among others—none of them entirely satisfactory for describing the geologic or ecological characteristics. From a hydrogeologic perspective, however, these ground-water dependent ecosystems can all be described by one simple term—ground-water slope wetlands—a name that captures two essential physical attributes: they always occur on or at the base of slopes, and their hydrology is supported by ground water. Other important implications of the term are that these wetlands are associated with hillside outcrops of some kind of aquifer (typically the Cameron Valley sand or terrace gravel in this region), and they comprise the discharge zones at the ends of local or regional ground-water flow systems in those aquifers.

The attentive observer can find small *seepage faces* at many places, typically in concave places along the lower parts of hillsides. Unfortunately, most are not in parks and have been degraded by changes in land use, so they do not possess the characteristic vegetation, even though the basic ground-water slope hydrology is still evident. Seepage swamps and other places of ground-water discharge observed during the course of the fieldwork for this project are noted on **plate 6**.

In addition to the more obvious wetlands, ground-water discharge of a somewhat more diffuse nature is responsible for the moist conditions that prevail throughout most of the major ravines (figure 6-17). There is typically a constant discharge of ground water along the toeslopes and stream banks in these ravines, producing the steady supply of moisture required to sustain mesic plant communities, amphibians, and related organisms and ecological communities requiring constant moisture. Chinquapin Hollow and Monticello Park are good examples of this kind of discharge: a traverse down either stream will reveal springs, seeps, and moist spots emanating from permeable sand lenses and fractured clay units in the Potomac Formation, and from various surficial sediments, such as *colluvium* and *alluvium*.

Figure 6-17. Seepage along streambanks, evident here from the iron staining just above water level, is an important process that contributes significantly to streamflow. The constant seepage of ground water softens the sediments and leads to the process of sapping, which contributes to the reshaping of streambanks and slopes over time. Photo by Rod Simmons.

Prior to its channelization, Cameron Run was perhaps the most spectacular example in the region of a large wetland complex sustained by both surface water and ground water. This stream formerly meandered through a broad valley that contained a variety of wetlands. In addition to large amounts of ground-water discharge from the valley walls, there was undoubtedly considerable interchange between surface water in the stream and shallow ground water beneath the wetlands and alluvial terraces fringing the creek. Although most of the natural hydrologic function of this valley has been obliterated by urbanization, some sense of what it was like can be gleaned from a few isolated places, such as the back of Cameron Regional Park, and an unnamed slough on the south side of Backlick Run opposite Cameron Station and Brenman Park. Large swales that cross parts of the Old Town terrace also appear to have been major swamps, but other than scattered hydrophytic trees, there is little left of these wetlands. Likewise, Oronoco Bay appears to have been a sizable *tidal marsh*, but it was completely filled in early in the city's history.


Figure 6-18. Cameron Run Valley and estuary (left), and Hume Spring (right) circa 1900, two historically important water features in the city's history. Photos courtesy of Alexandria Library, historical collections.

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